1.1. Definition of Terminology

Introduction to terminology

As light is pulsed into an optical fibre, and the backscatter collected, it means when assessing and optimising DTS performance for an application, a key point to remember is that the primary physics of the measurement are affected by:

- The optical loss of the system you are trying to measure
- The spatial sample you are taking along the length of the fibre (can set your optical budget limit), and
- The duration you collect the back scatter for.

In short the lower the optical loss, the longer the spatial resolution, and the longer you collect the backscatter data for the better/smoother the temperature resolution you will get as a result. However the practicality of an application may mean as a user you need more detail than this, and hence a selection of unit parameters is made based on a balance of the above 3 points.

The advantage of the Schlumberger solution is that we manufacture a range of fibre optic units, and have a regularly maintain support software package that gives the DTS user the ability to see both fast and slow averaged data.

Positional Resolution

Positional resolution (the same as sampling interval) is the distance between each measurement point along the fibre and therefore determines the total number of measurements on a given sensor fibre. Sampling at intervals smaller than the specified positional resolution (interleaving) enables the position of the hot-spot to be identified more accurately.

Fibre Length (Spatial Range)

The maximum length of the fibre sensor is defined as the spatial range and is the total length of the measurement. This is governed by the total two-way loss in such a length and must include the fibre loss; the loss in any point probes used, splice and connector losses. The two-way loss for each direction must be used since the signal of interest (the back scattered signal) travels the length of the fibre out and back. The ultimate limitation is the dynamic range of the DVS / DSTS itself - reached when the return signal is so weak as to be indistinguishable from the system noise - or limited by the bandwidth of the fibre. To determine the precise performance of the DVS / DSTS the total loss must be measured or calculated.

Range

This is the maximum length of optical fibre that the system can measure. Depending on the instrument type lengths over 25km may require optical amplification. This involves splicing passive remote optical amplifiers into the sensor fibre at the required intervals.

Frequency Range

This is the range of vibration frequencies that the DVS can detect. The maximum value for a particular installation will vary with the range being measured.

Event Types

The DVS will attempt to classify all the vibration signals it detects. These classifications are broken into event types that must be configured on the system.

Event Detection
The Schlumberger DVS is capable of discriminating between multiple simultaneous events occurring along the length of sensor fibre.

Measurement Time
This is the minimum time between the outputs of successive sets of events/profiles. This time includes acquisition of the backscatter signal, averaging and processing.

Spatial resolution (vibration)
The spatial resolution for the DVS instrument is defined as the shortest distance between two adjacent localised events which allows successful detection of each event.

Spatial Resolution and Sampling Interval (Temperature)
Spatial resolution is defined as: a step temperature change T is introduced at a point in the sensor fibre. When this step change is measured using the DTS it is blurred over a distance of the fibre. The actual distance between the 10% and 90% points of the step temperature change T is defined as the spatial resolution.

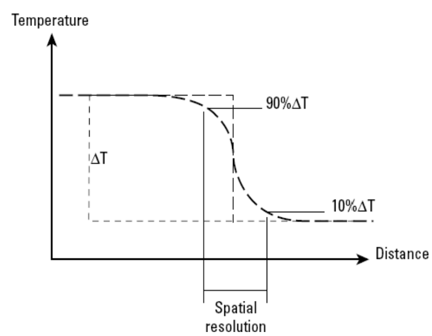

Figure 1 : Definition of spatial resolution

The response of the DTS to a local temperature excursion is explained with reference to Figure 2. When the temperature “hot spot” occupies a zone which is less than the spatial resolution of the DTS, the measured temperature is lower by approximately the ratio of (hot-spot width/spatial resolution). In applications where the width is known, a correction factor can be estimated.

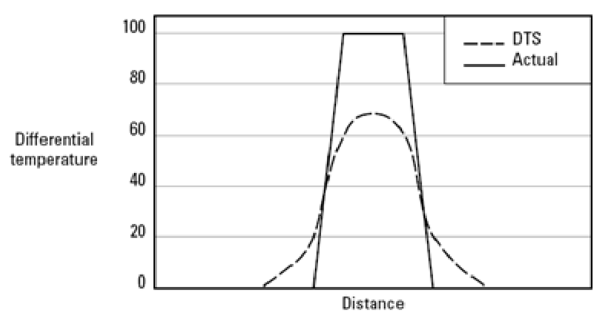

Figure 2 : Response of a DTS to a local temperature excursion

The sampling interval is the distance between each measurement point and this determines the total number of measurements on a fibre sensor (typically every 0.5m). A DTS point probe which contains fibre coiled on a former and packaged in a high thermal conductivity casing can be used to reduce the effective spatial resolution of a system

at individual points. This coil contains sufficient fibre so that the DTS accurately measures the temperature of the probe casing. The probes must be constructed with care in order to minimize excess losses and optimize thermal contact.

Temperature Accuracy

Temperature accuracy is defined as the residual error in the calculation of temperature assuming the signal has no uncertainty contribution from random noise sources. In other words, if temperature uncertainty due to signal noise were removed (e.g. by very long averaging cycles) the residual error in temperature is defined as the accuracy of the system.

Temperature Resolution

The temperature resolution specification is given as the RMS deviation of the measurement in a given measurement time. This removes the impact of peak to peak noise that can be miss leading.

Understanding the relationship between the DTS parameters:

The spatial resolution is fixed for the DTS acquisition unit (It can be varied by manufacturing). The temperature accuracy is effectively set by the calibration and with well-designed product not really affected by the system's operation. The response time and temperature resolution are linked. If the measurement period is reduced, the temperature resolution gets worse since the average time is reduced, the signal to noise ratio in the system will get worse. The rough rule is that for a 4 times increase in time, the temperature resolution will decrease by half.

For example, if a system has a temperature resolution of 2degC (RMS) in 10secs then this same system will have a 1degC temperature resolution in 40secs. Length (optical loss) is a factor as well; if the length is decreased, then the temperature resolution becomes better for the same measurement period.

The DTS dynamically adjusts its laser operating parameters to suit each individual fibre being measured. Consequently, the temperature resolution depends on many factors, including:

- The measurement averaging time
- The selected spatial resolution
- The effect of secondary averaging, if used
- The total length & loss of the optical fibre
- The level of additional, extrinsic losses (connectors, splices, fibre damage, etc.)
- The measurement mode (single-ended or double-ended)
- The distance to the point along the fibre where the resolution is measured

1.2. Distributed Temperature Sensing

The Raman DTS system operates using a variant of standard OTDR (Optical Time Domain Reflectometry) technology. The standard OTDR, operates using Rayleigh scattering. This is the term used for the component of light scattered at the same wavelength as the incident beam, and is the dominant scattered signal.

However, the interaction of the incident beam with the individual molecules in the fiber, which vibrate due to thermal excitation, causes two wavelength-shifted components of the incident signal to be scattered (Figure 3) and, in the same manner as the Rayleigh component, these are re-captured and returned to the interrogation unit. These two shifted components, the so-called Stokes and anti-Stokes components are separated by means of optical filters before electronic detection. The longer wavelength Stokes line is only weakly temperature sensitive, but the intensity of the backscattered light at the shorter anti-Stokes wavelength increases with temperature and the ratio of the intensities of the anti-Stokes and Stokes wavelengths can thus be processed to yield temperature information.

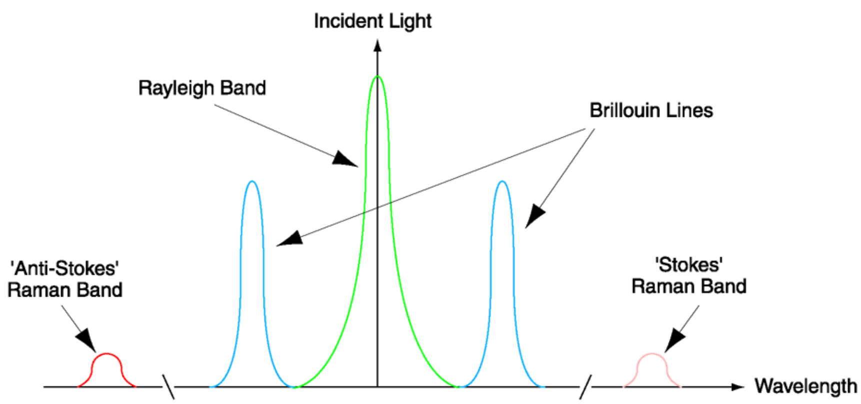

Figure 3: Principle of Operation: Highly Stylised Backscatter Spectrum, with Raman and Brillouin Wavelength-Shifted Components

The Schlumberger DTS can be configured to examine the raw data to provide a more meaningful interpretation according to the specific application. For instance, in a pipeline leak detection application, the DTS can scan the entire pipeline route, looking only for occurrences of temperatures below a preset threshold (such as would be caused by a leak of high-pressure gas). In this case the data reported by the DTS would not consist of a flow of temperature vs. position information, but would be reduced to an alarm signal, accompanied by data on local temperature, position and a timestamp for that leak only. In applications involving the monitoring of temperature along an asset (such as a heated flowline) then the data might then consist of a packet of data (consisting of a floating-point temperature value per meter along the pipeline) every 5 minutes.

1.3. Distributed Strain and Temperature Sensing

Stimulated Brillouin scattering occurs from the interaction between the probe pulse of light and thermally excited acoustic waves (phonons) within the fibre optic cable. The phonons can be generated via electrostriction which is an effect caused by the probe pulse of light. The exchange of energy (inelastic scattering) between the phonons and photons gives rise to a change in the frequency of the photon. This is a Doppler type effect due to the differing velocities and directions of the phonons and photons. By measuring the frequency of the photons, relative to their original state, we can determine the temperature or strain of the glass where the scattering occurred.

To measure the Brillouin frequency accurately requires making many measurements at slightly different optical frequencies. These measurement traces are combined and analysed to determine the Brillouin frequency at each measurement point along the length of each measured fiber. The DSTS is based on Brillouin Optical Time Domain Reflectometry (B-OTDR). Brillouin scattering arises from the interaction between incident photons and thermally generated lattice vibrations (phonons) in the medium in which the photons are propagating. In essence, the lattice vibration forms a temporary and transitory grating, which interacts with the probe light. If the acoustic wavelength of the phonon matches the optical wavelength of the incident photons then scattering can occur which re-directs the light in the return direction (in fact the scattering occurs in all directions, with the frequency of the scattered light depending on scattering angle). Typically, for a 1550nm probe wavelength, the frequency shift for the backscattered light is in the region of 10-11GHz and depends on the speed of sound, the refractive index and other parameters. As in Raman scattering both up-shifted (anti-Stokes) and down-shifted (Stokes) frequencies occur.

In spontaneous Brillouin scattering the intensity of the scattered light is proportional to that of the incident light. The DSTS operates in much the same manner as the Raman DTS, in that it measures the spontaneous Brillouin scattering and its distribution along the optical fiber sensor. However, the wavelength shifts of the Brillouin components are very much smaller than those of the Raman Effect, being of the order of 0.1nm. In this case, microwave signal extraction techniques are used (as opposed to the optical filtering employed in the Raman OTDR) to detect the wavelength shifts.

A distinctive feature of B-OTDR compared with Raman DTS is that the wavelength/frequency shift is sensitive to temperature and strain. By measuring the frequency shift in separate sensing fibers, the distribution of strain and temperature in the sensor fibers can be measured independently.

The output of the DSTS is a simple, calibrated table of results of temperature and/or strain (depending on measurement configuration) as a function of distance along the sensor fiber. Using this measurement data can yield useful information on the presence of:

1. Gas leaks - through the localised cooling arising from the Joules-Thompson effect of the escaping gas (in much the same way as described for the Raman DTS).
2. Oil leaks – where there is a temperature differential between the oil in a pipeline and the temperature of its surroundings.
3. Geohazards (ground settlement, landslides etc.) – by using a DSTS to interrogate a sensor cable (designed specifically to couple the strain arising from ground movement into a dedicated sensor fiber) the system can be used to detect, locate and measure the strain imposed on the cable as the ground moves. This is extremely sensitive and can be used as a warning of local geological activity before excess strain is imparted to the pipeline itself.

1.4. Distributed Vibration Sensing

The Heterodyne Distributed Vibration System (DVS) allows vibrations to be measured over 40 km and uses Rayleigh backscatter to determine changes along the fibre optic sensor.

The principle of operation in the DVS is substantially the same as the standard OTDR, operating as it does on the same Rayleigh backscatter principle. In commercial optical time-domain reflectometry instruments the laser source is selected with a coherence length shorter than the instrument spatial resolution, so that coherent noise is eliminated.

These would otherwise corrupt the desired backscatter slope and fibre uniformity data. For a vibration sensing application, the coherence length of the pulsed laser source is increased so that the coherence length is greater than the instrument launch pulse width, conditions for interference can be set up. This results in a system that becomes extremely sensitive to variations in fibre propagation conditions caused by external influences, with the additional and desirable ability to resolve position.

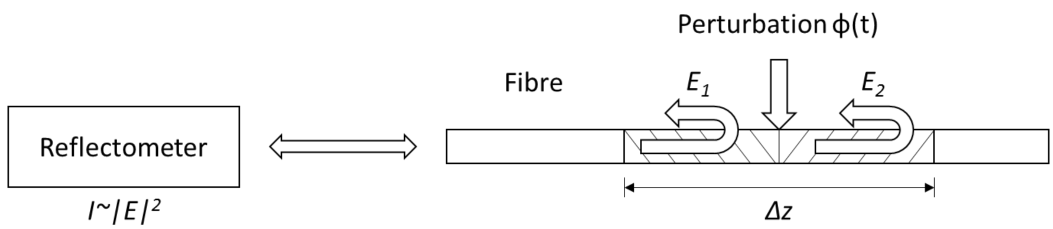

Figure 4: Principle of the DVS

Any mechanical or thermal disturbance in the vicinity of the sensing optical fibre will influence the optical path length experienced by the probe pulse of the DVS. For example, a person walking or a vehicle moving nearby the cable will cause vibrations at acoustic frequencies which will propagate in the ground, leading to corresponding dynamic strains in the sensor fibre. These strains will alter the instantaneous local interference conditions and cause the backscatter intensity from the affected section of fibre optic cable to vary dynamically. Sections of fibre not experiencing such disturbances will return a static backscatter signal.

In the centre of the section of fiber is a perturbation that causes a phase shift in the fiber. If the coherence length of the laser exceeds the spatial resolution of the DVS, then there will be interference between the return signals from the two halves, which can be detected by the optical receiver in the DVS. Although the instantaneous value of the interfered, backscattered, signals will be random, signal processing (averaging) can be used to extract the correlated interference data and hence detect and locate a time-varying disturbance.

Any mechanical or thermal disturbance in the vicinity of the sensor fiber will influence the optical path length (group index) experienced by the probe pulse of the DVS (through either dynamic strain or thermal expansion of the fiber itself). For example, a person walking or a vehicle moving nearby the cable will cause vibrations at acoustic frequencies which will propagate in the ground, leading to corresponding dynamic strains in the sensor fiber. These strains (at the nanostrain level) will, by altering the instantaneous local interference conditions, cause the backscatter intensity from the affected section of fiber to vary dynamically as the backscattered signal from the ensemble of scattering centers in the affected section of fiber varies from constructive to destructive interference. Sections of fiber not experiencing such disturbances will return a static backscatter signal.

1.5. Suggested Reference Reading

For more general information about DTS and DVS innovation we politely draw your attention to publications from the company that quite literally wrote the book on these techniques:

- G. Bolognini, A. Hartog, Raman-based fibre sensors: Trends and applications, Opt. Fibre Technol. (2013), http://dx.doi.org/10.1016/j.yofte.2013.08.003

- Hartog, A. H., L. B. Liokumovich, and O. I. Kotov, 2013, The optics of distributed vibration sensing, EAGE - Stavanger, EAGE, Second EAGE Workshop on Permanent Reservoir Monitoring.

- Optical Fibre Sensor Technology (Edited by K.T.V. Grattan and B.T. Meggitt), Chapman and Hall, London 1995, ISBN 0-412-59210-X: contributed Chapter 11: "Distributed Fibre-Optic Sensors".

- Optical Fibre Sensor Technology: Advanced Applications - Bragg Gratings and Distributed Sensors (Edited by K.T.V. Grattan and B.T. Meggitt), Kluwer Academic Publishers, Dordrecht 2000, ISBN 0-7923-7946-2. Contributed Chapter 4: "Distributed Fibre-Optic Sensors: Principles & Applications".

- Schlumberger In-house Manual - 2005 - The Essentials of Fibre Optic Distributed Temperature Analysis (Ask your local Schlumberger representative for a copy).